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METHANOL-FIRED FUEL CELL POWER SYSTEM FOR REMOTE APPLICATIONS

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1. Introduction

Remote areas of Alaska need reliable, efficient, and clean electric power generators for remote homes, telecommunications stations, weather stations, and pipeline, oil, and gas monitoring equipment. A methanol-fired fuel cell power system (FCPS) can meet these requirements, with the added benefits that it produces no harmful emissions that would damage the fragile Alaskan environment and uses a fuel that is already widely available in Alaska.

The goals of this project were:

- Design and build a methanol-fired proton exchange membrane (PEM) fuel cell power system to support a 10 kWh per day dynamic load and deliver up to 1 kW continuous, grid-quality AC power, with peaking to 1.5 kW.
- Develop a control system that provides seamless integration of the methanol reformer and the PEM fuel cell and provides automatic and safe operation.
- Test the steady state and dynamic performance of the system at the Schatz energy Research Center in Arcata, California.
- Deliver the completed brass-board system to the Arctic Energy Technology Development Laboratory at the University of Alaska, Fairbanks, Alaska, for final system qualification.

In this paper, we describe the results of preliminary testing of the steady state and dynamic response of the methanol reformer and the system design and operation. We also report the results of steady state and dynamic performance tests of the complete system at SERC and at the Arctic Energy Technology Development Laboratory, including an analysis of methanol-to-AC power system efficiency.

2. Reformer Testing

One of the major challenges in producing the fuel cell power system for this project was the integration of the IdaTech FPM™ 20 methanol reformer and the SERC 40-cell, 300 cm^2 PEM fuel cell stack. The SERC PEM fuel cell runs dead-ended on the

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hydrogen side with brief purges at timed intervals. Each purge releases about 1 standard liter (sl) of hydrogen in a 1 second interval, thereby temporarily increasing the hydrogen flow rate by about 60 standard liters per minute (slm). When the power demand on the fuel cell steps up or down, the stack current and consequently the hydrogen consumption immediately steps up or down proportionally. On the other hand, the reformer does not immediately respond to a change in control signal and so the reformer hydrogen production rate cannot closely match or track the fuel cell consumption rate.

After receipt of the reformer from IdaTech, we installed it on a test bench where we could communicate with the reformer's internal controller, measure the hydrogen production rate and pressure, and use a mass flow controller to simulate the fuel cell's hydrogen consumption rate and associated purges. With this setup we were able to become adept at using and controlling the reformer and to experiment with various approaches to integrating the reformer and the fuel cell.

We began by exploring how the reformer's steady state hydrogen production rate depended on the control signal to the reformer and the delivery pressure. Figure 1 shows the steady state hydrogen production rate vs. the control signal for three delivery pressures: 0, 10, and 20 psig. The control signal can range from 0 to 100.

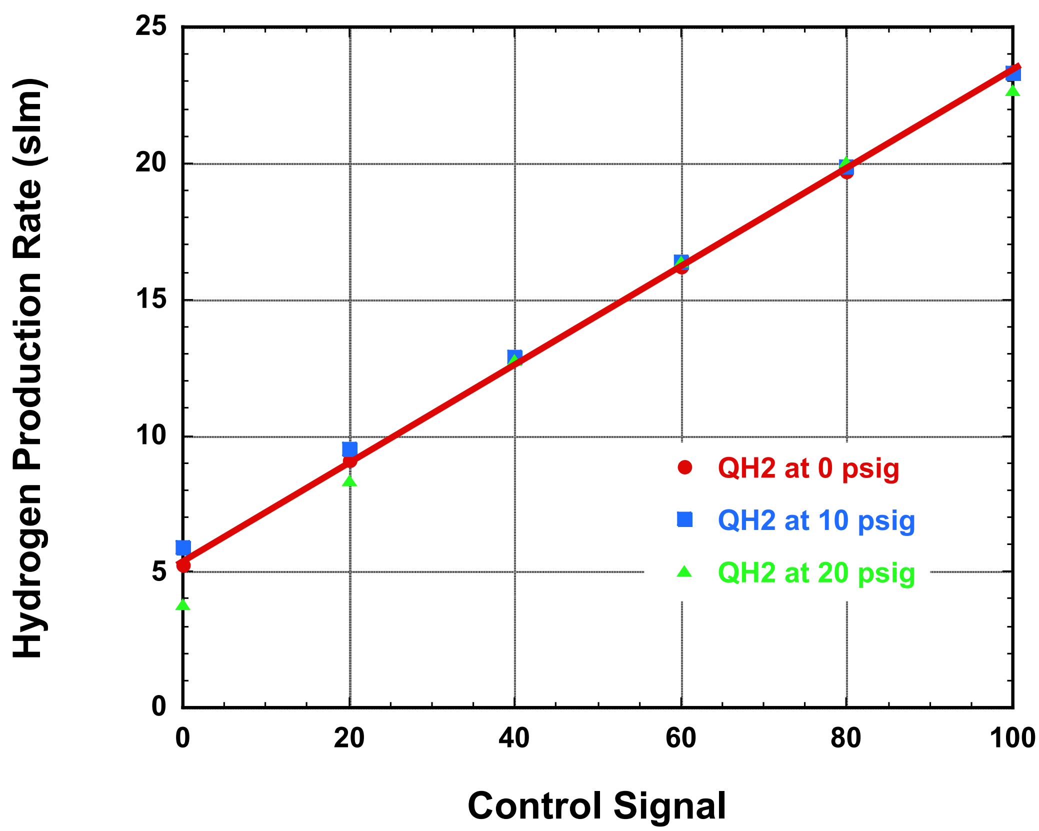

Figure 1. Steady State Hydrogen Production by IdaTech FPM™ 20
vs. Control Signal and Delivery Pressure

The hydrogen production rate varies no more than 2.5 slm over the delivery pressure range of 0 to 20 psig. At the maximum control signal of 100, the hydrogen production rate reaches an average of 23 slm, while at the minimum control signal the production rate averages 5 slm. The production rate is well approximated as a linear function of the control signal.

We next investigated the dynamic response of the reformer's hydrogen production rate to sudden step-wise changes in the control signal. Figure 2 shows how the hydrogen production rate changes over time as the control signal steps from 0 to 100 at delivery pressures of 0 and 10 psig. The reformer hydrogen production rate responds quickly to a step change in the control signal. The production rate approaches the steady state value exponentially with a half-life of 20 to 30 seconds.

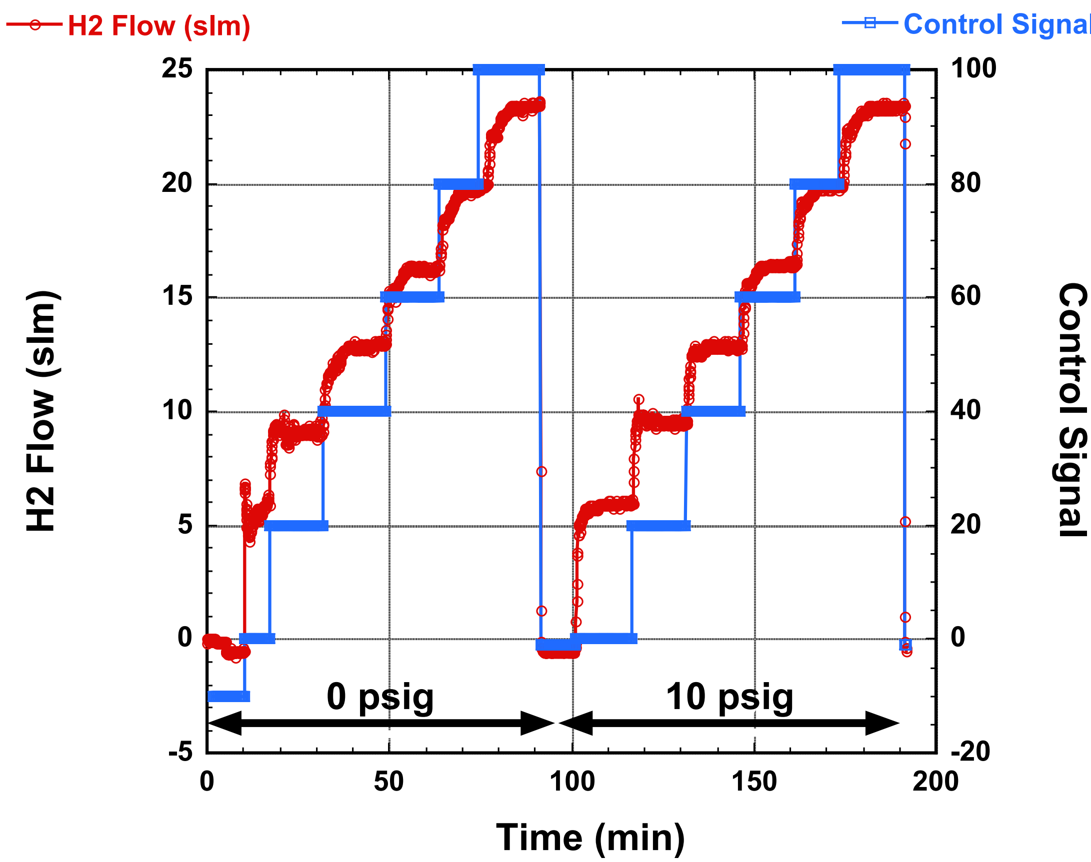

Figure 2. Dynamic Response of Hydrogen Production by IdaTech FPM™ 20

3. System Design

SERC selected, procured, and integrated all the air, water, hydrogen, electrical, and control system components for the system.

To manage the mismatch between the reformer hydrogen production rate and the fuel cell hydrogen consumption rate, we added a small, low pressure hydrogen ballast tank between the reformer outlet and the pressure regulator serving the fuel cell and we developed a reformer control algorithm. The ballast tank provides 10 liters of storage at 15 to 25 psig which corresponds to about 6 sl of active storage. The reformer control algorithm adjusted the control signal in response to measured ballast pressure and fuel cell current. Figure 3 shows a schematic of the methanol-hydrogen system with the ballast.

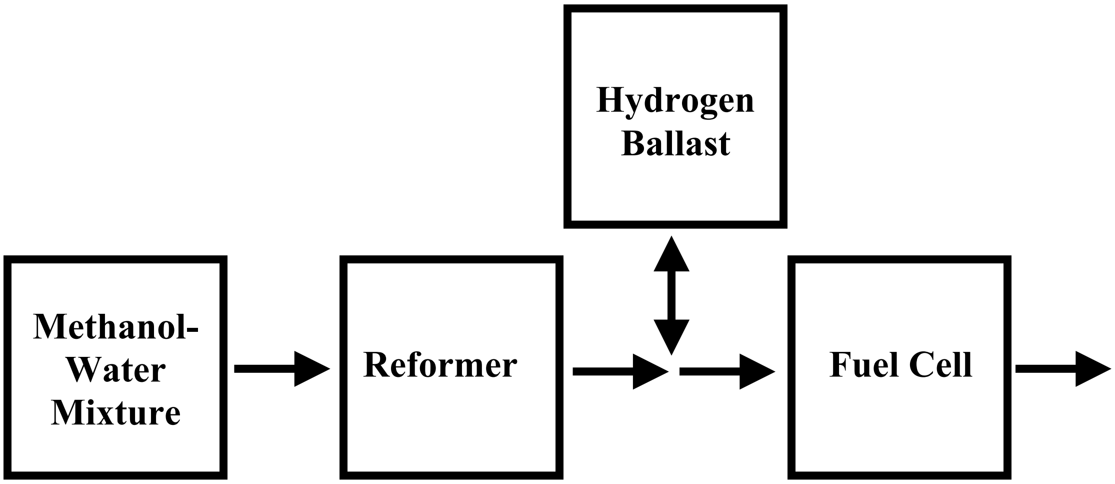

Figure 3. Schematic Diagram of Methanol-Hydrogen System with Ballast

Figure 4 shows a schematic diagram of the power handling system. The SERC 40 cell, 300 cm^2 PEM fuel cell generates 0 to 1000 W at 40 to 26 V. A high efficiency step-down dc-to-dc converter drops the voltage to 24 to 28.8 V. All parasitic loads are

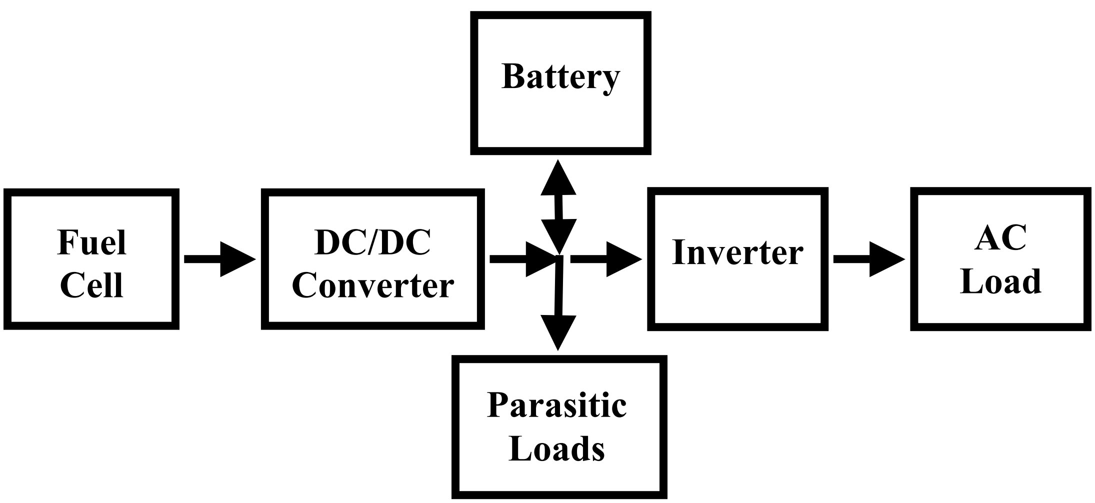

Figure 4. Schematic Diagram of Power Handling System

powered from this nominally 24 V bus. The battery is charged or discharged depending on the nominally 24 V bus voltage and serves as an energy ballast in the system. Since the response time of the fuel cell is limited by the response of the air supply system, the battery discharges and helps support the load during the air blower ramp-up period. After the air supply catches up with the power demand on the fuel cell, the battery is recharged. Finally, the ProSine 1000 inverter converts 24 Vdc to true sine wave 120 VAC and delivers up to 1000 W continuous and 1500 W during a surge.

The control system handles battery management, reformer control, fuel cell control, cell voltage monitoring, software dependent safety tasks, and data acquisition and recording. SERC developed the LabVIEW™ based control software in-house. The data acquisition and control system utilizes modular National Instruments Compact FieldPoint® hardware for all analog and digital input/output. Compact FieldPoint® hardware is suitable for control, measurement, and signal processing in stand-alone embedded real-time systems. The hardware is rugged, capable of withstanding 50 g shocks, 5 g vibrations, and tolerant of –25 to 60°C conditions. An ethernet interface is available for convenient program uploading and data downloading. The system also incorporates a software independent safety circuit that monitors a hydrogen detector and a smoke detector and will immediately shutdown the complete system if a hazardous condition is detected.

The completed system is a preproduction prototype or brassboard system built on a small lab bench. In order to facilitate access during system development, subsystem components (e.g., hydrogen supply, water/cooling, power management, etc.) were assembled on panels or shelves that were then installed as a unit on the system bench. Figures 5, 6, and 7 show views of the completed system from the front, side, and rear. In Figure 5, the fuel cell, air blower, methanol storage, methanol reformer, hydrogen ballast, and the power rack with control panel and battery bank are all visible and labeled. In Figure 6, many components of the hydrogen subsystem are shown and labeled, including the methanol storage tank, the hydrogen delivery line from the reformer, the hydrogen pressure transducer, the pressure regulator, the hydrogen supply solenoid valve, the hydrogen delivery line to the fuel cell, the purge solenoid valve, and the hydrogen purge/knockout drum. In Figure 7, the rear of the system is shown and the major components of the water subsystem are labeled, including the water reservoir, the water pump, the deionizing bed, and the water delivery and return lines to and from the fuel cell stack.

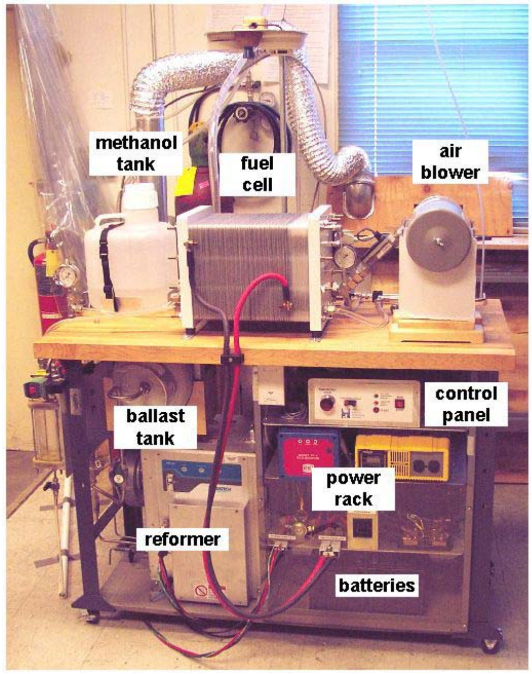

Figure 5. Front View of Completed System Showing Fuel Cell, Air Supply, Methanol Storage, Reformer, and Power Rack with Control Panel

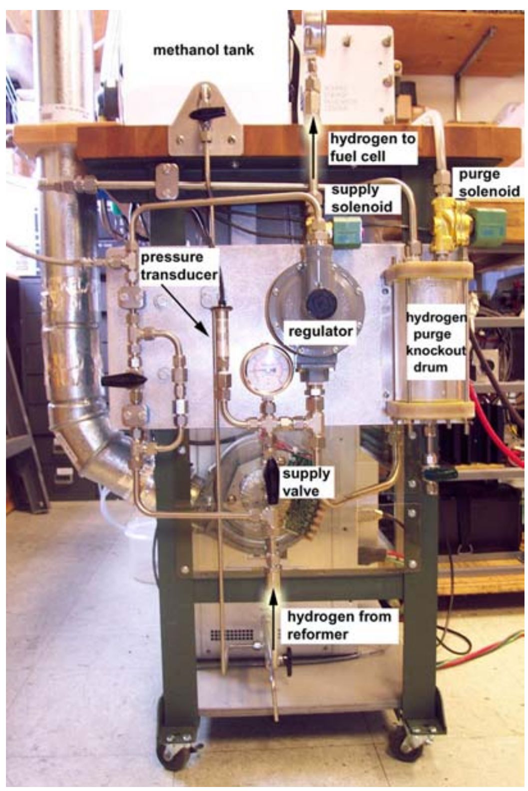

Figure 6. Side View of Completed System Showing Hydrogen Subsystem

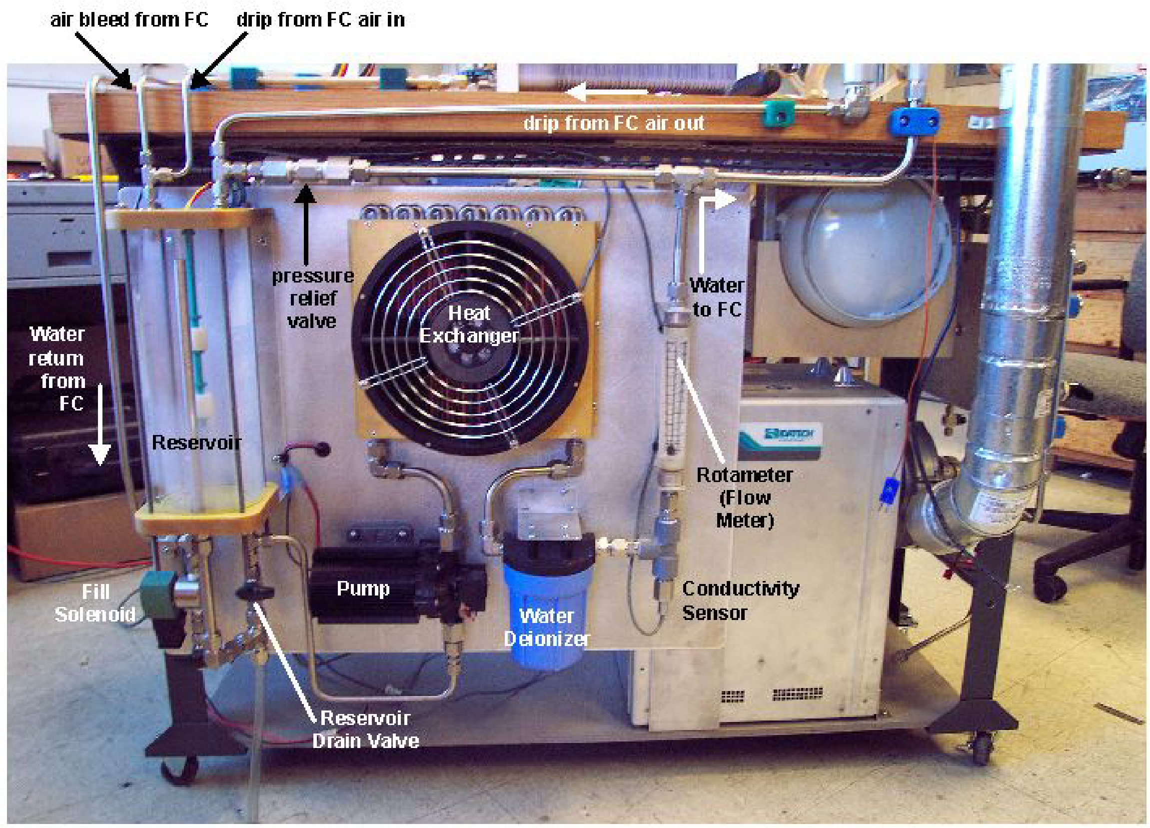

Figure 7. Rear View of Completed System Showing Water/Cooling Subsystem

4. System Testing at SERC

After assembly of the system, low level tests were conducted on all analog inputs, analog outputs, digital inputs, and digital outputs to verify their proper operation and calibration. Then the system was tested under constant AC load at 1000 W for 9 hrs and 400 W for 72 hrs.

Figure 8 shows fuel cell power output, power in and out of the battery, and the dc power input to the inverter over the 9 hrs of testing at 1000 W AC load. During the first 35 minutes after system power-up, the reformer goes through a start-up sequence, drawing about 150 Wh from the battery bank and consuming about 0.5 L of methanol/water fuel mixture from the storage tank. When the reformer is ready, the fuel cell starts and the 1000 W AC load is connected. Initially the fuel cell must both support the AC load and recharge the battery bank that was discharged during reformer start-up. The power input to the inverter is always lower than the power output from the fuel cell due to parasitic loads and battery charging. The fuel cell output is stable with no decay over the 9 hours of testing.

Figure 9 displays the results of a 72 hr test with a continuous load of 400 W AC. This corresponds to continuous loads associated with cathodic protection of gas and oil

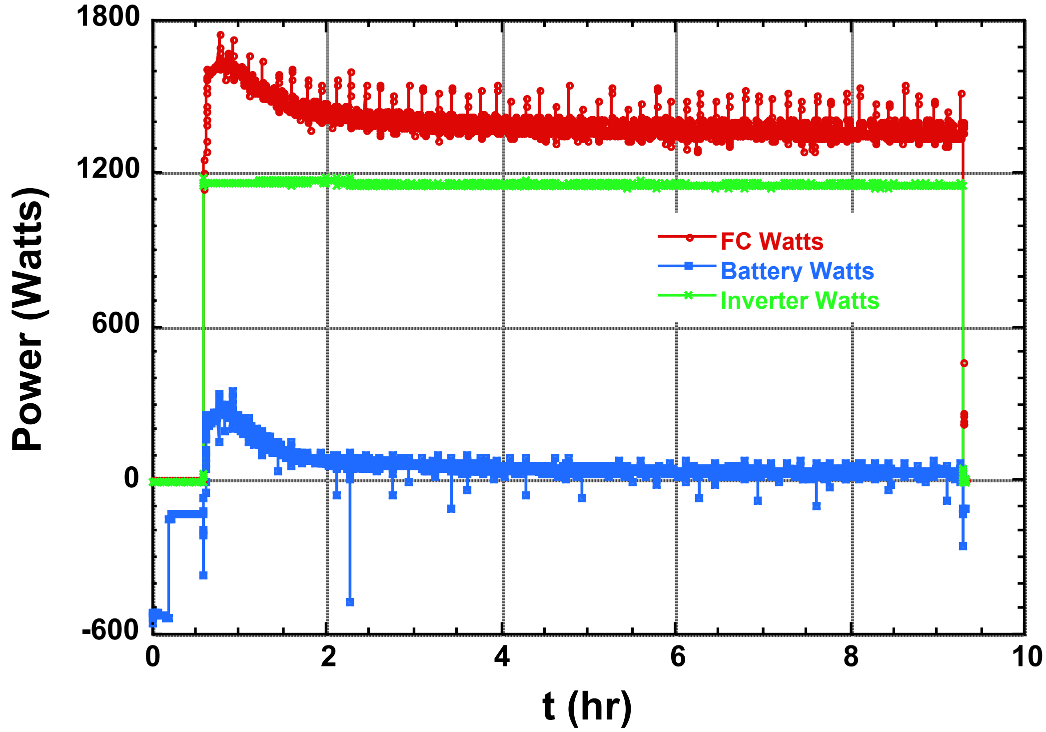

Figure 8. Fuel Cell Output, Battery Input/Output, and Inverter Input Power during 72 hrs of Continuous Operation at 1000 W AC

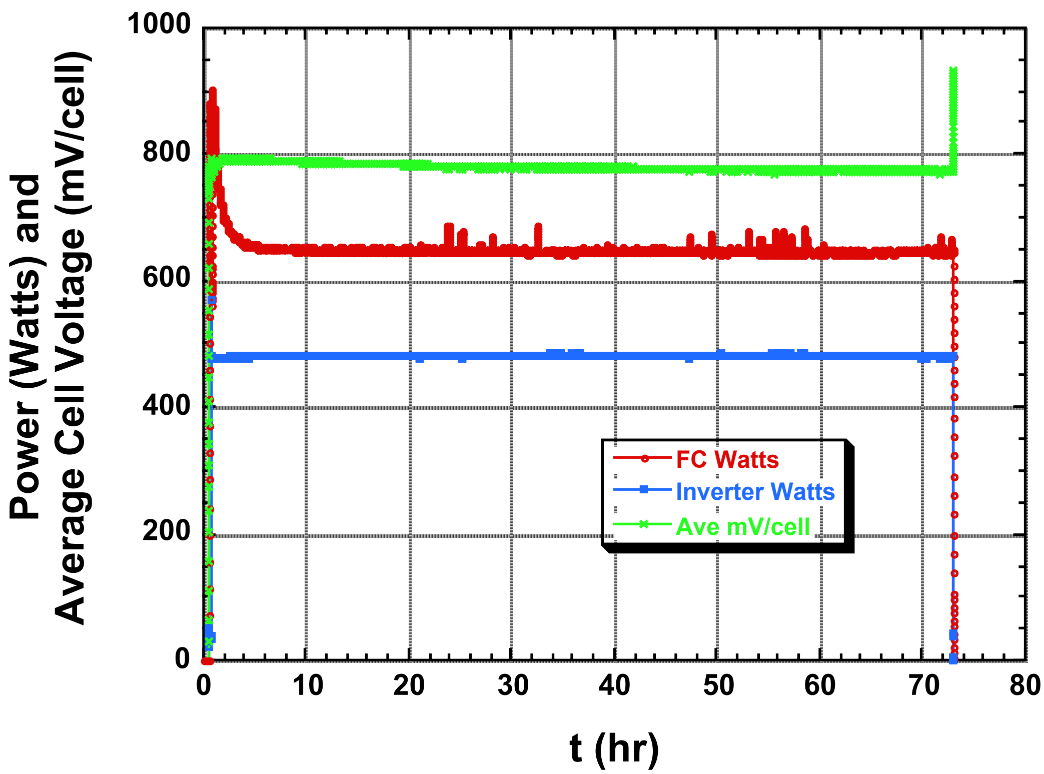

Figure 9. Fuel Cell and Inverter Power and Average Cell Voltage at 400 W AC for 72 hr

pipelines and also approximates the daily power consumption for a remote home (e.g., 9.6 kWh/day). In the plot, fuel cell power output, inverter power input, and the average cell voltage for the fuel cell stack are shown for the 72 hr continuous run. The system performed well with minimal decay in average cell voltage.

Next the system was tested under dynamic AC load. Figure 10 shows the results of a test with progressively increasing load from 0 to 1000 W AC in steps of 100 W over a 6 hr period. The plot shows the fuel cell power output, inverter power input, and the average cell voltage for the fuel cell stack. The system quickly and smoothly responds to each 100 W increase in load while the average cell voltage drops less than 100 mV/cell. Note that the fuel cell output during the first two load steps reflects both the power required to support the load and the power needed to recharge the battery bank which was discharged during reformer startup.

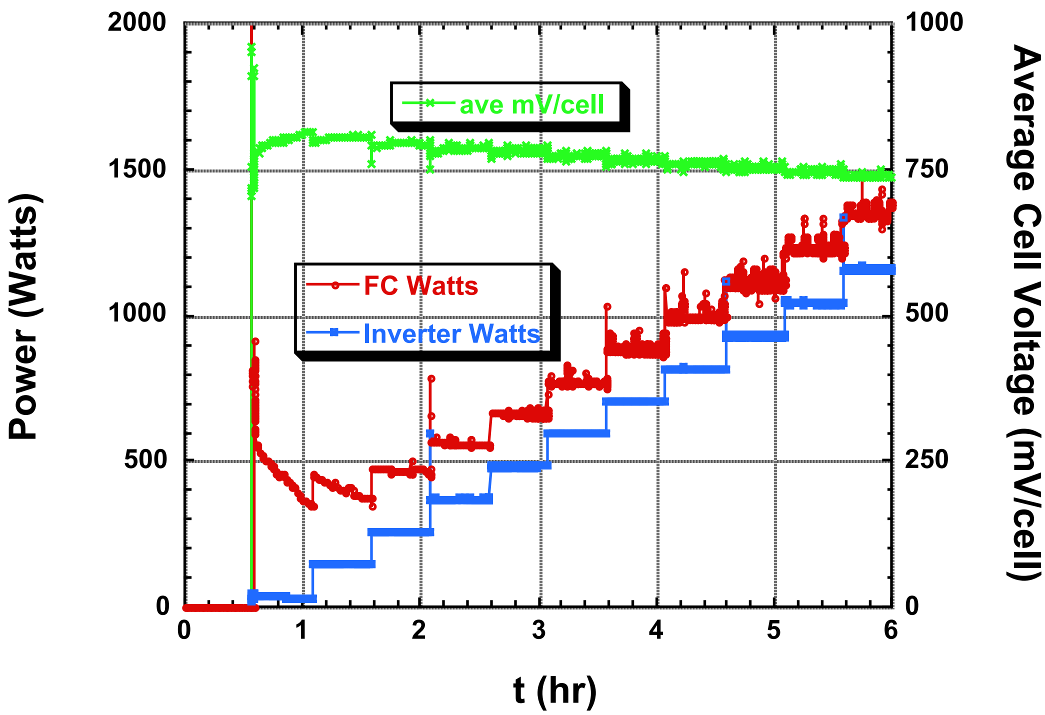

Figure 10. Fuel Cell and Inverter Power and Average Cell Voltage at Progressively Increasing AC Loads from 0 to 1000 W in Steps of 100 W

Additional dynamic load testing was conducted to record system response to inductive loads and complex dynamic loads cycles that mimic diurnal load patterns observed in residences. In all cases the system performed well. In the inductive load tests, the battery bank delivered power to the inverter during the brief period required for the air blower to ramp up and was then quickly recharged by the fuel cell.

5. System Testing at the Arctic Energy Technology Development Laboratory

Following completion of testing at SERC, the system was crated and shipped to Fairbanks for further testing at the Arctic Energy Technology Development Laboratory at the University of Alaska. Figure 11 shows the system ready for testing in Fairbanks.

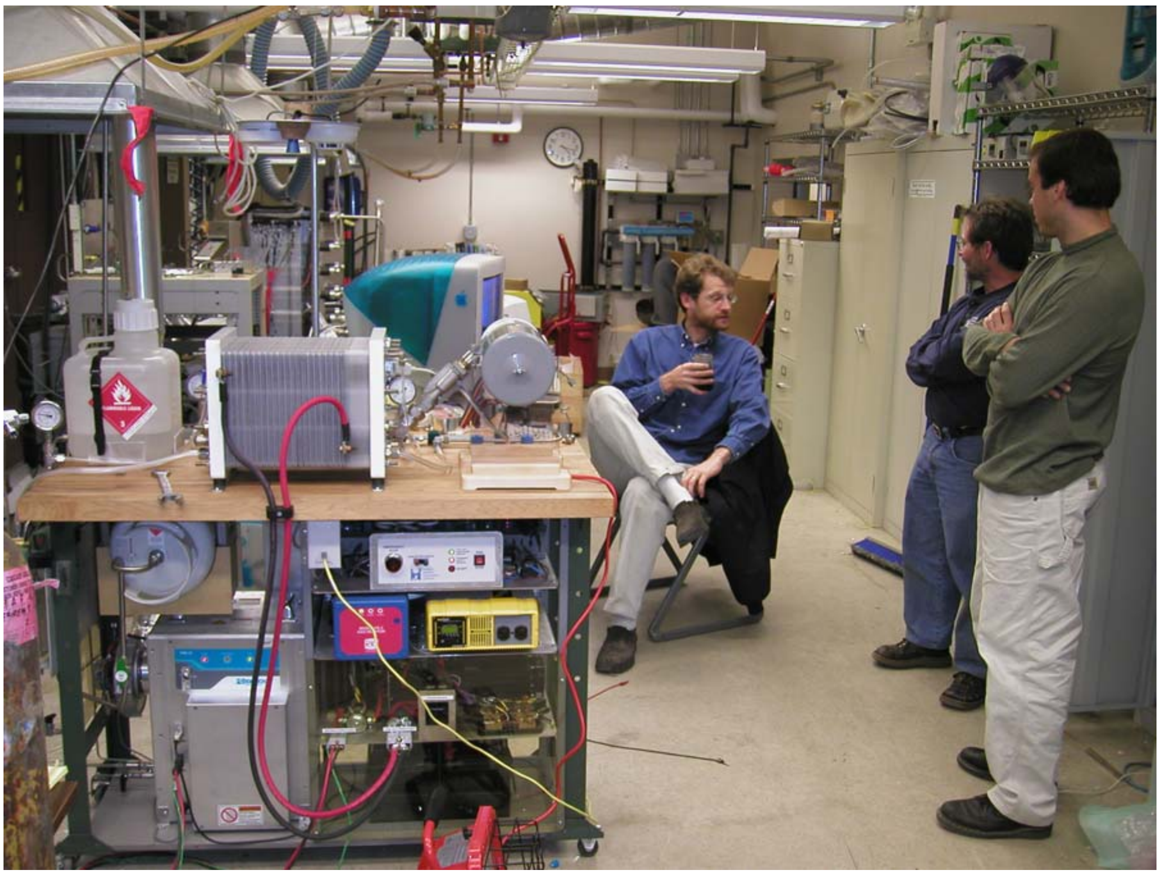

Figure 11. System ready for testing at Arctic Energy Technology Development Laboratory at the University of Alaska, Fairbanks. UAF research engineer Tom Johnson, SERC engineer Mark Rocheleau, and UAF graduate student Tristan Kenny are shown from left to right.

The testing set-up at AETDL included a methanol/water fuel flow sensor and a AC power transducer in addition to the sensors incorporated in the fuel cell power system. Figure 12 shows the results of a dynamic load test using 2+ sequential 24 hr load cycles that mimic a 12 kWh/day residential energy usage pattern. Fuel cell power output and the inverter AC power output are shown for the 52 hrs of testing. The fuel cell power output smoothly tracks the step-wise changes in load. Figure 13 shows the methanol/water fuel flow and the AC load for the same run.

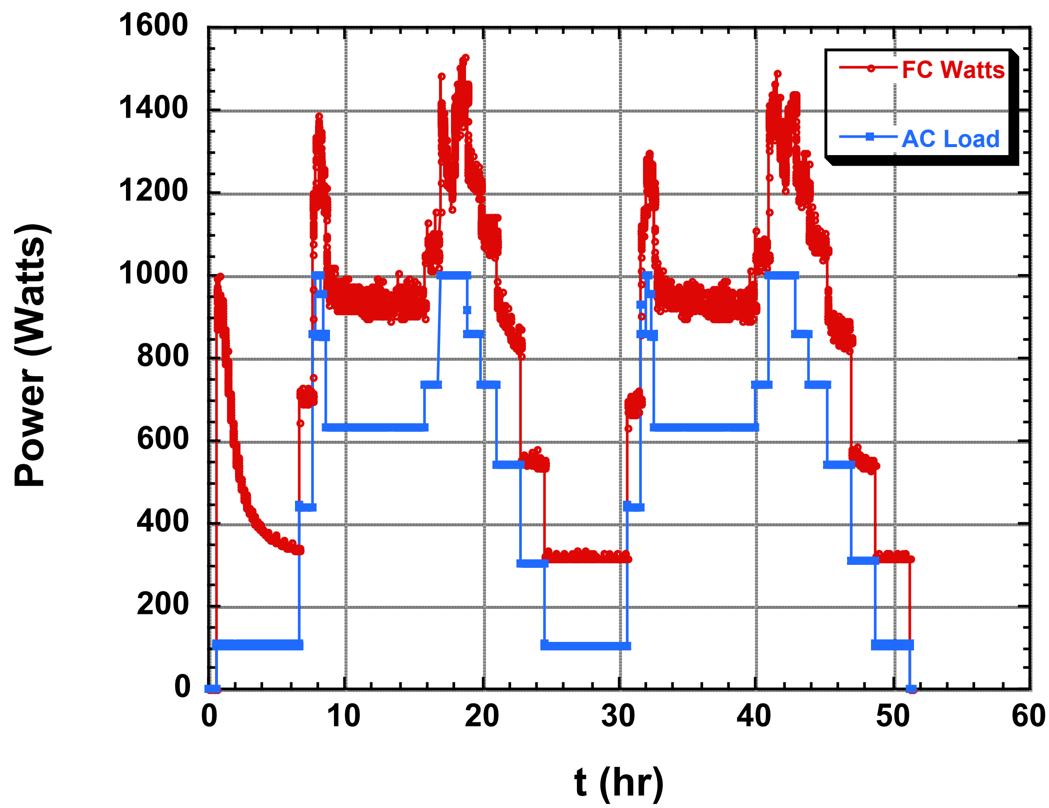

Figure 12. Fuel Cell Power and AC Load for 48 hr Load Cycle Test at Arctic Energy Technology Development Laboratory

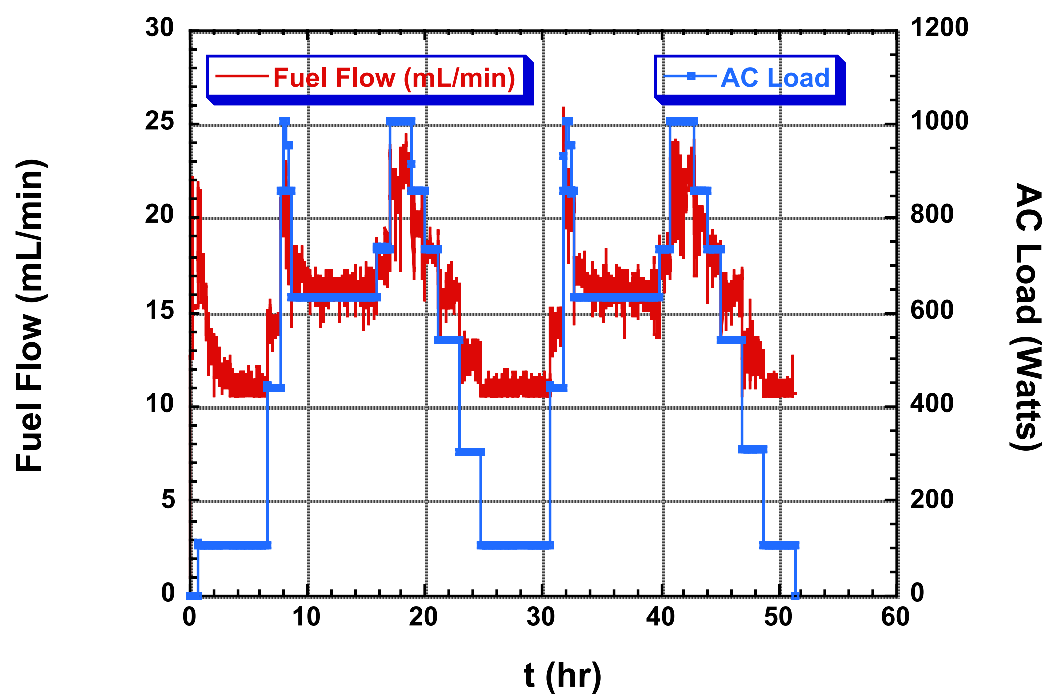

Figure 13. Fuel Flow and AC Load for 48 hr Load Cycle

6. System Energy Flow and Efficiency

Using the results of the 9 hr constant load test at 1000 W and the 48 hr dynamic load tests, we computed for periods of constant load the energy equivalent (LHV) of the fuel flow into the reformer and the hydrogen output from the reformer, the energy output from the fuel cell, the net energy input to the battery, the energy input into parasitic loads, the energy input to the inverter, and the AC energy output from the inverter. Figure 14 shows the corresponding schematic diagram for the system energy flow.

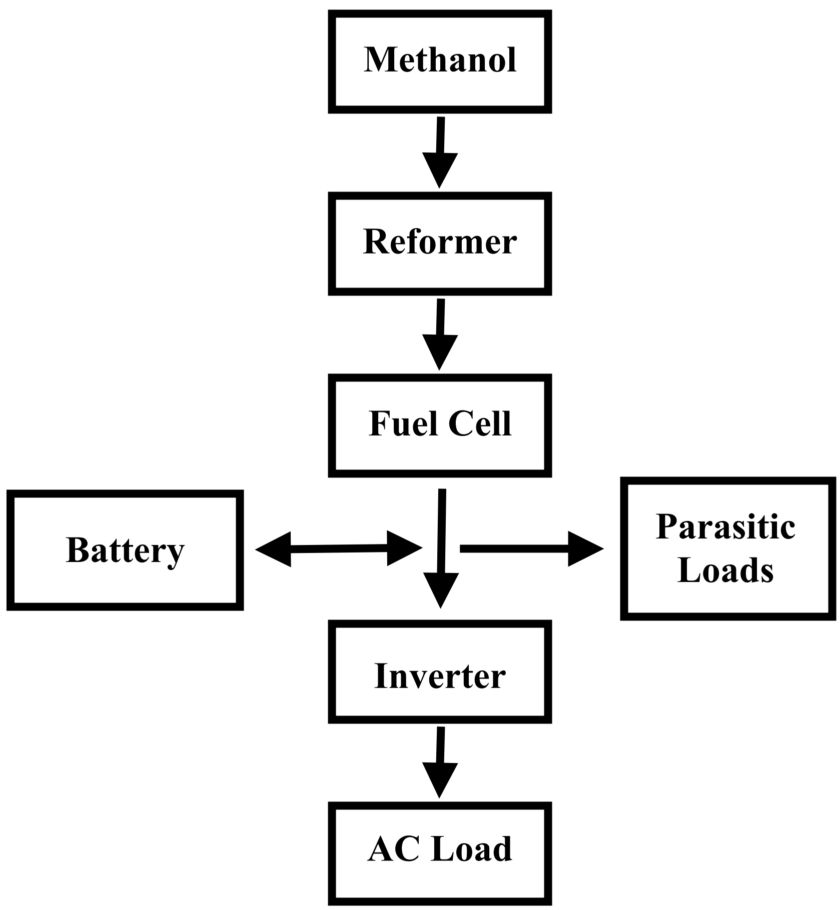

Figure 14. Schematic Diagram of System Energy Flow

Based on the results from the 9 hr constant load test at 1000 W (i.e., the maximum rated system power output) following reformer start-up, Table 1 summarizes the average energy flow rates at each step in the energy flow diagram, the fraction of the energy provided by the methanol that remains at each step, and the unit efficiencies of the reformer, fuel cell, and inverter. The net input to the battery bank is negligible (i.e., 1.3% of the fuel energy and 3.9% of the fuel cell output). Parasitic loads average

Table 1. Summary of System Energy Flow and Efficiency by Conversion Step

Conversion Step	Energy Flow (Watts)	Cumulative System Efficiency (%)	Unit Efficiency (%)
Methanol Consumption Rate	4084	100.0%	
Reformer Hydrogen Output	2463	60.3%	60.3%
Fuel Cell Output	1356	33.2%	55.1%
Net Battery Input	53	1.3%	
Parasitic Loads	185	4.5%	
Inverter Input	1157	28.3%	
AC Power Output	1000	24.5%	86.4%

only 4.5% of the fuel energy (and only 13.6% of the fuel cell output). The average efficiency of the reformer was 60.3%, the fuel cell 55.1%, and the inverter 86.4%.The overall average system efficiency, methanol in to AC power out, was 24.5%, which is good performance in comparison to other reformer/fuel cell power systems.

In the 48 hr test with a dynamic load cycle, we conducted a similar analysis for each discrete power level in the load cycle so that we can examine the relationship between system AC load and the overall system efficiency, methanol in to AC power out. Figure 15 presents this relationship. As the system AC load increases from 0 to 1000 W, the overall system efficiency increases from 0% (at zero power out) to about 25% at full load (1000 W). Overall system efficiency remains about 20% down to about 650 W load. The solid line in Figure 15 is the fit of the data to the following model:

$$E = E_{max} \cdot \left(1 - e^{-k \cdot P}\right) \tag{1}$$

where:

E = overall system efficiency (%)

E_{max} = maximum overall system efficiency (%) = 28.7%

k = empirical coefficient (W^{-1}) = 0.00196 W^{-1}

P = system AC load (W)

This model fits well, with a R^2 value of 99.7%.

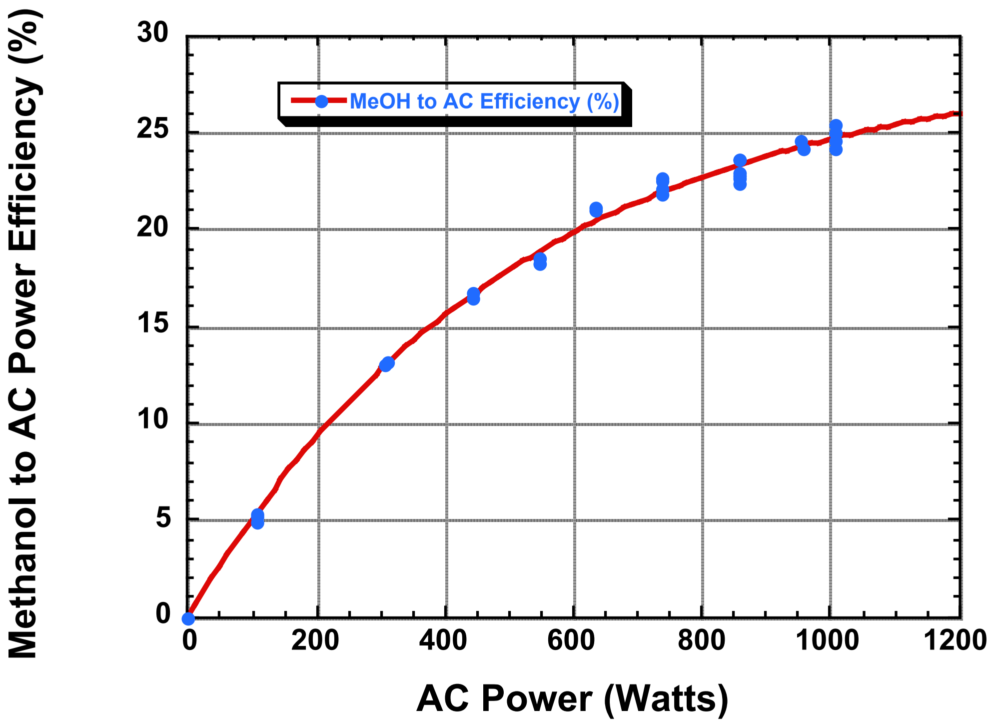

Figure 15. Overall System Efficiency vs. AC Power Output

7. Conclusions

In this project we:

- designed and built a methanol-fired proton exchange membrane (PEM) fuel cell power system that can support a dynamic load in excess of 12 kWh per day and deliver up to 1 kW continuous, grid-quality AC power, with peaking to 1.5 kW.
- developed a control system that provides seamless integration of the methanol reformer and the PEM fuel cell and provides automatic and safe operation.
- tested the steady state and dynamic performance of the system at the Schatz Energy Research Center in Arcata, California and at the Arctic Energy Technology Development Laboratory at the University of Alaska, Fairbanks, Alaska.
- observed stable performance of the system in tests up to 72 hrs with negligible drop in average cell voltage.
- found that the system was able to instantaneously and smoothly respond to stepwise changes in load and to inductive loads.
- demonstrated an excellent overall system efficiency of 24-25% at full load (1000W) and good efficiency of 20% at partial load (650 W).

Our next step is to install the system in a residence or small business and monitor its performance in long term operation.